

# Experimental indication of anomalous sensitivity in many-body systems: Deterministic randomness in complex quantum collisions?

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We have experimentally tested a recently suggested possibility for anomalous sensitivity of the cross sections of dissipative heavy ion collisions. Cross sections for the  $^{19}\text{F}+^{27}\text{Al}$  dissipative collisions were measured at the fixed energy 118.75 MeV of the  $^{19}\text{F}$  for the 12 different beam spots on the same target foil. The data demonstrate dramatic differences between the cross sections for the different beam spots. The effect may indicate deterministic randomness in complex quantum collisions. New experiments are highly desirable in a view of the fundamental importance of the problem.

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For classical chaotic systems infinitesimally small uncertainties in the initial conditions are exponentially enhanced after a certain time making long time dynamics unpredictable. This unpredictability is referred to as dynamical instability of motion or deterministic randomness [1]. On the contrary, quantum systems with finite number of degrees of freedom, whose classical counterparts are chaotic, are dynamically stable with respect to small changes of the initial state. Such a stability is also expected with respect to infinitesimally small perturbations of the quantum systems. Indeed, effect of a small perturbation on an excited quantum system is quantified by its strength,  $|K|$ , as compared to the average level spacing  $D$  of the system. Here  $K$  are matrix elements which couple unperturbed states by the perturbation. From the perturbation theory, for  $|K|/D \ll 1$ , the perturbation produces only a little effect on the system.

Alternative consideration [2] of the complex collisions has suggested an anomalous sensitivity of the cross sections to the extremely small perturbation of the intermediate complex (IC) [3]. In particular, the perturbation with a strength  $|K| \sim 10^{-4}D$  or even smaller may result in  $\pm 15\%$  variations of the cross sections of dissipative heavy ion collisions (DHIC). The consideration [2] is intimately related to, and provides an interpretation for, the channel-channel correlation and nonself-averaging of the excitation function oscillations in DHIC. A spontaneous character of setting up the cross sections was supplemented by effect of the non-equilibrium phase transitions for channel-channel correlations in DHIC [4], which is essentially a quantum interference phenomenon. In [2], the small perturbation was modeled by changing the number of electrons moving in Coulomb field of the IC. However,

if the effect of the anomalous sensitivity does exist, this would imply other intriguing possibilities. For example, one may experimentally study effects of chemical structure of the target and its phase, e.g., crystalline or amorphous, on the cross sections. Yet, before designing such experiments, one has to experimentally address the problem of the reproducibility of the cross sections for nominally identical conditions in different experiments. This is because even nominally identical target foils have different distributions of electromagnetic fields, defects, etc. Such a non-reproducibility has indeed been revealed in the two independent experiments [5]. However, because after the first measurement [5] the reaction chamber was dismantled it may not be excluded that some experimental conditions could change for the second measurement.

The fundamental importance of the problem has motivated us to test the anomalous sensitivity of the cross sections in a new experiment without opening the reaction chamber. Measurements of differential cross sections of fragments B, C, N and O produced in the DHIC  $^{19}\text{F}+^{27}\text{Al}$  have been carried out at the China Institute of Atomic Energy (CIAE), Beijing. The beam of  $^{19}\text{F}^{9+}$  at incident energy 118.75 MeV was provided by the HI-13 tandem accelerator, CIAE. Two sets of gas-solid ( $\Delta E$ -E) telescopes, with a charge resolution  $Z/\Delta Z \approx 30$  and an energy resolution  $\approx 400$  keV, were set at  $\theta_{lab}=57^\circ$  and  $31^\circ$ . The angular acceptances of the telescopes were  $\delta\theta = 17.5^\circ$  and  $\delta\phi = 3.1^\circ$  for  $\theta_{lab}=57^\circ$ , and  $\delta\theta = 6.4^\circ$  and  $\delta\phi = 1.3^\circ$  for  $\theta_{lab}=31^\circ$ . The  $\Delta E$  detector is an ionization chamber filled with a mixture-gas of 90% argon and 10% methane in flowing mode at a pressure of 100 mb. The residual energy is deposited in a Si detector with a thickness of 500  $\mu\text{m}$ . The low energy thresholds of the  $\Delta E$ -E telescopes were about 7,8,9 and 11 MeV for

the B, C, N and O fragments respectively. Two silicon semiconductors arranged at  $\theta_{lab} = \pm 7.5^\circ$  were employed to monitor the beam, and a Faraday cup was placed at  $\theta_{lab} = 0^\circ$ . The  $\Delta E$ -E telescopes, the monitors and a Faraday cup were placed in the reaction plane. A  $10 \times 50$  mm rectangular  $^{27}\text{Al}$  foil was produced with vacuum evaporation method [6]. Its average thickness of  $\simeq 67 \mu\text{g}/\text{cm}^2$  corresponds to 180 keV beam energy loss in the target. Before the experiment the target thickness was measured with  $\alpha$ -particle thickness gauge using the air equivalent method [6, 7] at 22 different target points with the step 2 mm along the straight line on which 12 beam spots, in the following experiment, were located. Relative variation of the thickness did not exceed 8%. The total energy spread due to the beam energy spread (45 keV) and the beam energy loss in the target (180 keV) was about 225 keV, i.e. about a characteristic energy length of the oscillations in the excitation functions for the  $^{19}\text{F} + ^{27}\text{Al}$  DHIC [8]. Thus, fine energy resolution in our experiment allows to resolve the energy oscillating component of the cross section, which is suggested to be responsible for the anomalous sensitivity of the cross sections [2].

In the measurement, 12 target points were bombarded by moving the rectangular target in steps of 2 mm along a fixed direction perpendicular to the reaction plane. After the experiment the target thickness was measured again at each of the 12 beam spots having a diameter of about 1 mm which is close to the beam diameter on the target.

At the beginning of the experiment we have measured angular distributions of the B, C, N and O fragments at the  $E_{lab} = 114$  MeV incident beam energy (Fig. 1). The angular distributions were obtained by integrating over the whole outgoing spectra. As an example, in Fig. 1 we present energy spectrum for the N products at  $\theta_{lab} = 31^\circ$  obtained for one of the 12 beam spots. The angular distributions and the spectrum show characteristic features of DHIC [8].

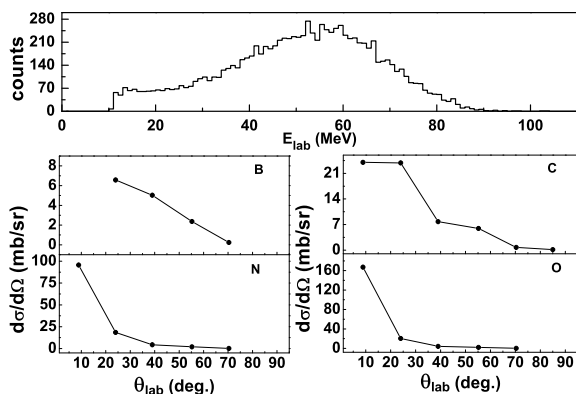


FIG. 1: Top: Energy spectrum of the N fragments at  $\theta_{lab} = 31^\circ$ . Bottom: Angular distributions of the B, C, N and O fragments (see text).

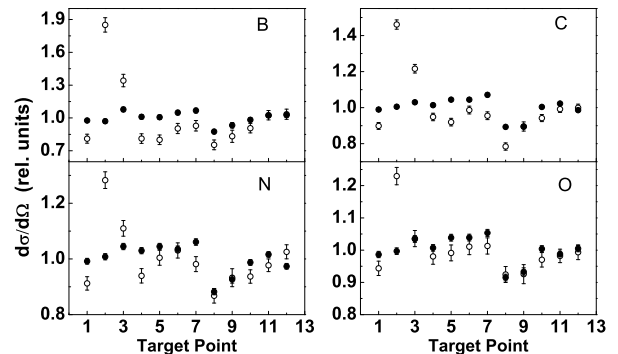


FIG. 2: Cross sections of the dissipative fragments B, C, N and O at  $\theta_{lab} = 57^\circ$  (open circles) and  $31^\circ$  (filled circles) for the 12 different target spots (see text).

In Fig. 2 we present the cross sections (in relative units) at the 12 different beam spots. These cross sections were obtained by integrating all the counts of the energy spectra. The cross sections were normalized as follows. For each reaction fragment and angle, at a given beam spot, we divide the total number of the counts by the solid angles of the telescopes and by  $(M1+M2)/2$ , where M1 and M2 are the counts of the silicon semiconductors. This allows us to scale out effects of variation of the target thickness for different beam spots. Deviations of the ratio M1/M2 from unity for different beam spots did not exceed 4%. Then, for each fragment and angle we obtain 12 numbers, which are 12 cross sections (in relative units), corresponding to the 12 beam spots. We scale these 12 numbers (with the same scaling factor for given fragment and angle) such that the average over the 12 cross sections is unity. This procedure was applied for each fragment and angle. In Fig. 2 the error bars are given by  $\pm 1/N^{1/2}$ , where  $N$  is a number of counts in the energy integrated spectrum, for each fragment and angle, at a given beam spot. These numbers  $N$  are generally different for different fragments, angles and beam spots.

We also use another method to obtain the cross sections in Fig. 2. For each reaction fragment and angle, at a given beam spot, we divide the total number of the counts by the target thickness at this beam spot, by Faraday cup charge counts and by the solid angles of the telescopes. Again, for each fragment and angle we obtained 12 numbers, which are 12 cross sections (in relative units), corresponding to the 12 beam spots. We scale these 12 numbers to have the average over the 12 beam spots equal to unity, for given fragment and angle. This procedure was applied for each fragment at each angle. We found that both methods produce the data which agree within the statistical accuracy. The cross sections in Fig. 2 are clearly not the same for different beam spots. To quantify the cross section variations, in Fig. 3 we plot the probability distributions of absolute values of the deviations of the cross sections for each fragment and

angle, at different beam spots, from the average value of unity. The deviations are scaled with the  $1/N^{1/2}$  factors, where  $N$  is a number of counts in the whole spectrum for given fragment and angle at each beam spot. If these deviations originated from a finite number of the counts the probability distributions would be Gaussian with a standard deviation of unity. However the data are scattered on a much wider interval. Indeed, the probability for deviations greater than three standard deviations is 50% for 5 cases in Fig. 3, and 33.33%, 25%, 8.33% for the rest 3 cases. The corresponding probability for the Gaussian distribution is 0.27%.

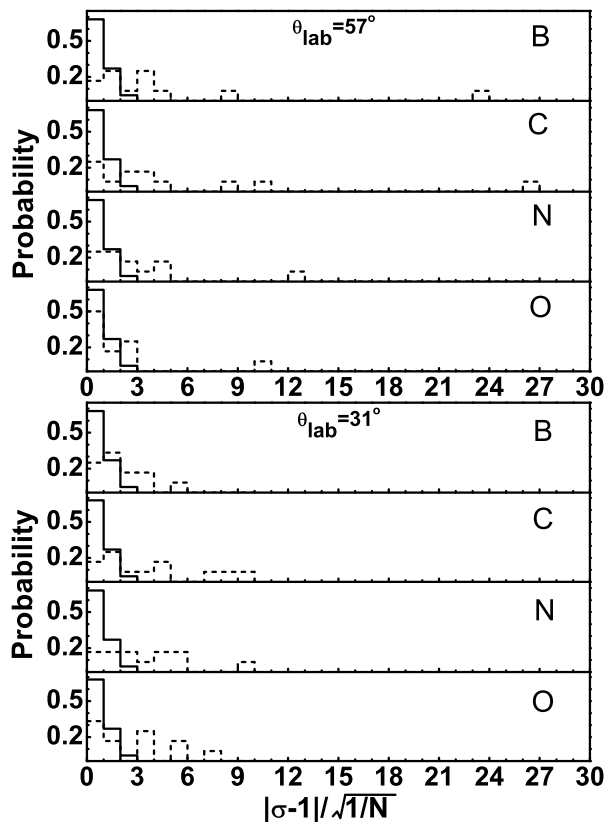


FIG. 3: Dotted histograms: Probability distributions of absolute values of the measured relative cross sections deviations from averaged value of unity for the B, C, N and O fragments at  $\theta_{lab} = 57^\circ$  and  $31^\circ$ . Solid histogram: Gaussian distributions with a standard deviation of unity (see text).

In Fig. 4 we plot the probability distribution for the deviations from the average unity of the cross sections summed over all the fragments and angles. For each beam spot, we sum 8 previously obtained partial cross sections (in the relative units) to obtain the summed cross section. We apply this procedure for each of the 12 beam spots. As a result we obtain 12 numbers which are the summed cross sections in relative units. We normalize these cross sections such that the cross section averaged over all the 12 beam spots is unity. In Fig. 4, absolute

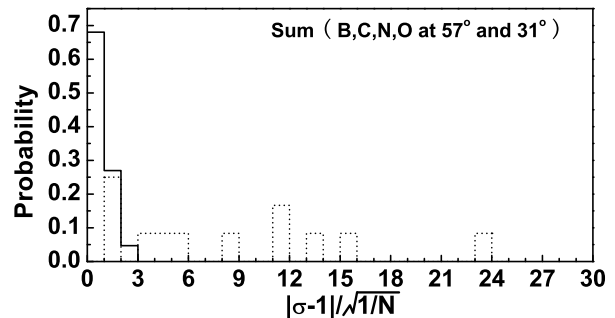


FIG. 4: Dotted histogram: Probability distribution of absolute values of deviations of the measured summed cross sections from averaged value of unity. Solid histogram: Gaussian distribution with a standard deviation of unity (see text).

values of the deviations of the cross sections, measured at different beam spots, from the averaged value of unity are scaled with the  $1/N^{1/2}$  factors, where  $N$  is a sum of the counts numbers for all the fragments and angles at a given beam spot. In this way, for each of the 12 beam spots, we increase the total number of counts resulting in a much better statistics of the data as compared with the analysis in Fig. 3. In Fig. 4 we also plot Gaussian distribution with a standard deviation of unity. This Gaussian distribution is expected if finite number of counts would be the only source for the deviations. We see a dramatic spread of the data in Fig. 4 as compared with the Gaussian distribution. Indeed, the probability for deviations more than four standard deviations is 67%, i.e. four orders of magnitude more than the value of 0.006% expected from the Gaussian statistics with a standard deviation of unity. We conclude that the experimental data do indicate a statistically significant dramatic non-reproducibility of the cross sections for different beam spots. In some cases the measured cross sections differ up to a factor of 1.5-2 for different beam spots (see Fig. 2).

Notice that visible correlations, for each individual angle, between the cross sections corresponding to the different fragments is consistent with the interpretation [2]: Though the B, C, N and O cross sections summed over very large number of exit channels have different random components for different beam spots these cross sections set up in a correlated manner for a given angle. A smaller amplitude of the cross section variations at  $\theta_{lab} = 31^\circ$  as compared to that for  $\theta_{lab} = 57^\circ$  is explained by the bigger relative contribution of direct-like processes for forward angles. This is because cross sections of the direct-like processes are stable with respect to very small perturbations. For  $\theta_{lab} = 57^\circ$ , the decrease of the amplitude of the cross sections variations with increase of the difference in mass numbers between the ejectiles and the projectile F is because the smaller this difference is the more are the relative contributions of direct-like processes.

The interpretation of the obtained results is based on a picture of formation of the IC with strongly overlapping resonances and a very slow phase relaxation between the coherently excited states with different total spin values [2]. The intrinsic excitation energy of the IC,  $E^* \simeq 20$  MeV, is obtained by subtracting the deformation energy,  $E_{def} \simeq 20$  MeV, and the rotational energy for the spin values close to grazing orbital momentum,  $E_{rot} \simeq 55$  MeV [8], from the total excitation energy  $E = 95.14$  MeV. For  $E^* \simeq 20$  MeV,  $D \simeq 10^{-7}$  MeV. We evaluate the effective strength,  $|K|$ , of the “target-environmental” perturbations to be of order of the atomic electron effects in DHIC [2]. These perturbations are due to the different distributions of electro-magnetic fields, defects, etc. for the different beam spots. From [2], we obtain  $K \sim \pm 10^{-6} D \simeq \pm 10^{-7}$  eV, which about 13 orders of magnitude less than the effective nucleon-nucleon interaction! Such small perturbations may be considered as nominally “infinitesimally small”. Yet, it was suggested [2] that even such small perturbations may strongly affect the cross sections. The basic point of the interpretation [2] is that the cross sections summed over very large number of exit channels are determined by the values and signs of the quantities  $N_H^{1/2} < \phi_\mu^J | \phi_\nu^I >$ , where  $N_H \rightarrow \infty$  is a dimension of Hilbert space and  $< \phi_\mu^J | \phi_\nu^I >$  are scalar products of the many-body resonance eigenstates  $\phi_\mu^J$ ,  $\phi_\nu^I$  with different total spins  $J \neq I$  and  $\mu, \nu$  being running indices. The  $\phi_\mu^J$  and  $\phi_\nu^I$  are orthogonal, i.e.  $< \phi_\mu^J | \phi_\nu^I > = 0$ . Then, applying a proper procedure, in the limit  $N_H \rightarrow \infty$ , the quantities  $N_H^{1/2} < \phi_\mu^J | \phi_\nu^I >$  are uncertainties [9]. The anomalous sensitivity of the cross sections occurs provided these uncertainties do not vanish. But then the values, in particular, the signs of the  $N_H^{1/2} < \phi_\mu^J | \phi_\nu^I >$  are set at random implying that the cross sections are unpredictable [10]. This also demonstrates that an infinitesimally small perturbation, which leads to infinitesimally small changes of the  $\phi_\mu^J$  and  $\phi_\nu^I$ , can change the signs of the uncertainties thereby resulting in a very large change of the cross section [2]. If so, the effect indicates deterministic randomness in complex quantum collisions which occurs due to the instability with respect to infinitesimally small perturbations.

Usually, an effect is considered to be reliably established if it can be reproduced in independent measurements with nominally identical experimental conditions. We realize that the experimental data presented in this Letter are in contradiction with this conventional point of view. Instead, we deal with “reproducible non-reproducibility” for the different nominally identical experiments. Namely, the effect can be considered as a real one provided the non-reproducibility of the cross sections will be confirmed in new independent experiments performed at other tandem accelerators. No matter how the interpretation [2] may be viewed, the importance of the

presented *experimental results* is far beyond the nuclear physics field calling for a new line of thinking. In view of the fundamental role of deterministic randomness in classical physics for the understanding of statistical laws, in particular statistical relaxation, from dynamics [1], it is highly desirable to test a possible deterministic randomness in quantum many-body systems in new experiments. “No matter how negligible the probability, in view of the thousands of experiments already done, any new possibility like quantum chaos should be used carefully to check the fundamental equations in the laboratory again and again” [1]. Our results do present a real possibility for the new and unexpected phenomenon of instability of the cross sections is complex quantum collisions.

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- [9] A possible way to quantify the uncertainties is to carry integration in the scalar products over the whole integration volume except an arbitrary located infinitesimally small element of this volume  $\Delta V$ . Then, the properly taken limits  $N_H \rightarrow \infty$ ,  $\Delta V \propto 1/N_H^{1/2} \rightarrow 0$  lead to (i) recovery of the scalar products and, (ii) non-vanishing of the uncertainties (S.Yu. Kun, work in progress).
- [10] This is especially clear for digital computer calculations for which the  $< \phi_\mu^J | \phi_\nu^I >$  do not vanish exactly due to the finite accuracy. Then, the signs of the  $N_H^{1/2} < \phi_\mu^J | \phi_\nu^I >$  are unpredictable in principle. A similar argument is often used to illustrate the impossibility of predicting long-time evolution of classical chaotic systems due to the unavoidable computational errors [1].